Modular Composition of Human Gaits Through Locomotor Subfunctions and Sensor-Motor-Maps

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Abstract. Human locomotion is a complex movement task, which can be divided into a set of locomotor subfunctions. These subfunction comprise stance leg function, swing leg function and balance. Each of these locomotor subfunctions requires a specific control of individual muscles in the human body. We propose a novel method based on sensor-motor-maps to identify the appropriate motor control settings based on sensory feedback loops. Based on template models, both the biomechanical as well as the neuromuscular dynamics of gait can be studies and described at different levels of detail.

1 Introduction

Legged locomotion is a daily activity in humans, which is crucial for a good living quality. In the case of limb impairments or even limb loss several treatments including orthotic and prosthetic systems can help to restore locomotor function. Recently, the German amputee long jumper Markus Rehm [1, 2] succeeded to outperform non-amputee long jumper and won the German championship using a highly elastic carbon fiber Cheetah prosthesis.

A prosthetic limb can be considered as a model for the substituted leg function. In the case of Rehm, lower leg function was replaced by a highly elastic carbon fiber spring. The comparable performance of Markus Rehm and non-amputee elite jumpers shows the role of elastic stance leg function in the take-off phase of long jump.

2 Locomotor Subfunctions

We consider legged locomotion to be composed of three locomotor subfunctions. The first subfunction is **stance leg function**, comprising axial loading and unloading of the limb. This leg function can be described by a prismatic spring and is represented by the spring-loaded inverted pendulum model [3]. In this highly simplified template model, regions for stable walking and running can be predicted depending on the forward speed, leg stiffness and leg angle of attack. The second subfunction is the **swing leg**

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function. Here, the leg realigns for the next touch-down. This rotational leg adjustment can be described by the action of thigh muscles acting like antagonistic springs [4].

The third locomotor subfunction is **balance**. Here, the goal is to keep the body orientation aligned upward. This can be achieved based on vestibular sensory feedback providing a reference for body posture in space. An alternative way for maintaining postural balance was suggested by Maus et al. [5]. Here the leg forces are aligned to point to a virtual pivot point (VPP). During human walking, the ground reaction forces intersect at this specific point, which is located in the upper body above the center of mass. This VPP concept can be easily implemented in biomechanical models for walking and running. It was shown to provide postural balance during locomotion. Recently, this concept was transferred into the FMCH concept [6], which assumes leg force-modulated compliant hip muscles to achieve balance. This was implemented in a model, which predicted similar hip torque patterns as previously obtained with the VPP model [5]. In human walking, such a linear dependency of hip torques normalized to leg force on the hip joint angle (Fig. 1) was found for a large range of walking speeds [7].

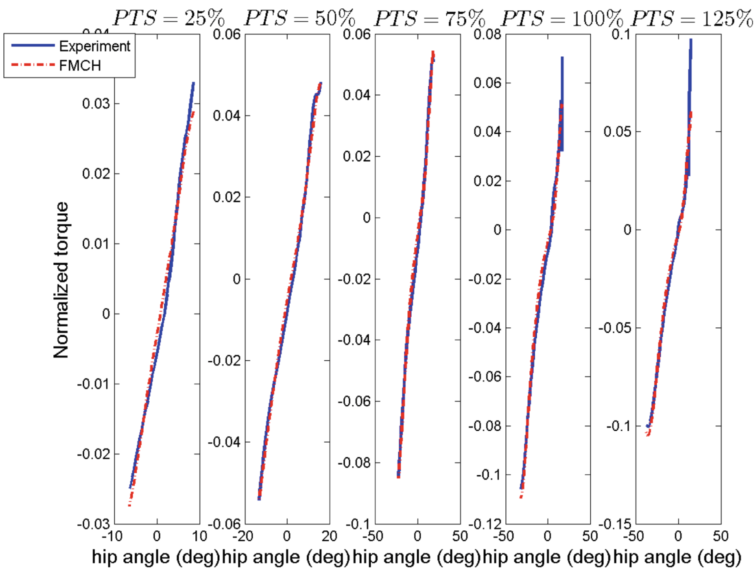

Fig. 1. Hip torques normalized to leg force as a function of hip angle during different walking speeds (25 to 125% of preferred transition speed, PTS, between walking to running gait). The predictions of the FMCH model match well the experimental data.

3 Sensor-Motor-Maps

In the last section, locomotor subfunctions were described on the mechanical level using physical leg, joint or muscle parameters. In the next step, we shift our focus to the neuromuscular description of the axial stance leg function. However, also for the other locomotor subfunction (balance, swing leg function) matching neuromuscular models can be identified. This research is, however, not yet completed.

The existence of biomechanical template models (e.g. SLIP, VPP) may suggest matching low-dimensional neuro-muscular control models. Then the neural system could take full benefit of the dimension reduction provided on the mechanical level. Assuming the leg spring model to represent the stance leg function, a matching neural control structure could be a reflex pathway based on sensory information (e.g. from muscle spindles or Golgi organs). The leg spring is described by a few parameters (leg stiffness, rest length of the unloaded spring). Similarly, reflex pathways can be characterized by reflex gain and offset. In both cases we find a similar algebraic structure.

For walking and running, the SLIP model predicts different combinations of leg stiffness and angle of attack to result in stable locomotion. Similarly, we can now study combinations of different reflex pathway parameters to achieve a continuous series of rebounds like in human hopping (or running). As different reflex pathways may lead to stable hopping, we consider a blending scheme integrating muscle force, length and velocity feedback with optimized gains and offset values [8]. All stable solutions can be represented in the so-called sensor-motor-map (Fig. 2B) indicating compact regions of appropriate blended feedback pathway combinations. The corners represent ‘pure’ muscle force, length and velocity feedback, respectively.

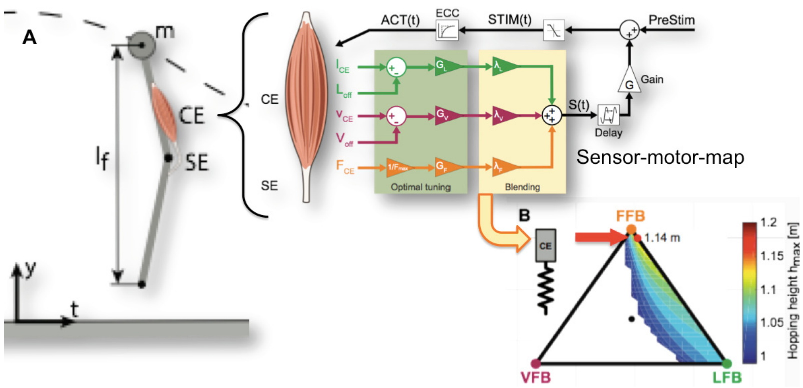

Fig. 2. The sensor-motor map (B) represents possible combinations of reflex pathways based on proprioceptive muscle sensory information (fiber length L, fibre velocity V and muscle force F). Here, one monoarticular extensor muscle is considered during hopping (A). The muscle is modeled as a serial arrangement of the contractile element (CE) and the serial elastic element (SE). The reflex signals from the different sensors are superimposed, time delayed and fed back to stimulate the muscle together with the prestimulation signal *PreStim*.

Similar to the region for stable running regarding leg stiffness and leg angle of attack, also on the neuro-muscular level different combinations of the three blended reflex pathways can be used to predict energetically stable hopping. Please note that the biomechanical SLIP model is energetically neutral, hence it cannot be used to address energy stability during locomotion.

The analysis of the neuromuscular hopping model reveals that stable hopping requires dominant force or length feedback pathways. The force feedback pathway is able to optimize hopping performance (i.e. maximum height, [9]) whereas length feedback increases hopping efficiency (i.e. metabolic costs in relation to hopping height). Velocity feedback is disabling hopping. Already a moderate contribution of the velocity reflex is sufficient to interrupt the cyclic movement transferring the system into a resting configuration. This establishes a safety measure as it enables a sudden controlled stopping of the movement.

The region for stable hopping found in the sensor-motor map is robust with respect to morphological changes, such as changed body mass, segment lengths and tendon or ground compliance. This indicates that the task-specific selection of sensory reflex pathways is universal and not much dependent on specific system properties.

4 Conclusion

In this paper we describe the modular organization of the biomechanical and neuromuscular system during legged locomotion with the help of locomotor subfunctions and sensor-motor-maps. The underlying assumption is that complex movement tasks can be decomposed into a set of elementary subfunctions. Each of these subfunctions requires an appropriate matching blending of the neuromuscular reflex pathways, which can be represented with the help of sensor-motor-maps. We described the biomechanical template models for two locomotor subfunctions (stance and balance) and the corresponding sensor-motor-map for stance leg function during hopping. To finally approve these concepts, all locomotor subfunctions need to be represented on both the biomechanical and neuromuscular level. It is required to prove that all subfunctions can work in parallel without losing their ability to fulfill their specific tasks. Finally, these concepts need to be applied to a robot testbed to prove their validity in real world. After successful approval, a transfer to assistive systems such as prosthetic or orthotic systems becomes feasible.

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